

1 **Identifying hydro-climatic and socioeconomic forces of water scarcity through**
2 **structural decomposition analysis: a case study of Beijing**

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14 **Abstract:**

15 Water scarcity has become a serious problem in many parts of the world. While many previous
16 studies have recognized that the changing water scarcity levels were attributed to population
17 growth, economic development and climate change, effects of different factors on variations of
18 water scarcity were rarely disentangled and quantified based on historical data. This study
19 develops an analytical framework, based on the structural decomposition analysis, to
20 decompose temporal water scarcity changes into effects of a number of hydro-climatic and
21 socioeconomic factors. The methodology is applied to water scarcity analysis in Beijing, China,

which has long been under severe water scarcity. Results from Beijing show that the population-driven water scarcity tends to increase, whereas the demand-driven water scarcity presents a slightly declining trend. The declining trend of demand-driven water scarcity is mainly attributed to industrial structure upgrade, improved water use efficiency, reclaimed and transferred water uses, and domestic water saving. In contrast, the economic development, population growth and increased ecological water use contribute to aggravating Beijing's water scarcity. High randomness in Beijing's water scarcity is mainly attributed to variability of available water resources. The results provide an in-depth understanding of dynamics in water demand and supply, and help develop policies towards sustainable water resources planning and management.

Key words: decomposition analysis; hydro-climatic factor; socioeconomic factor; trends; water scarcity indicator; water resources management.

1 Introduction

Water is vital for the survival and development of human society. While water is a renewable resource, its availability is finite in time and space due to the circulation rate in the climate system (Oki and Kanae, 2006). Nowadays, many countries/regions/cities in the world are faced with water scarcity (Vorosmarty et al., 2000; Islam et al., 2007; Wada et al., 2011). Lack of sufficient water resources may affect adequate access to safe drinking water, food security, economic development and health of ecosystems. Around two-thirds of the global population are now living in conditions of severe water scarcity for at least one month of the year, and half a billion people face severe water scarcity all year round (Mekonnen and Hoekstra, 2016). Moreover, water scarcity in many parts of the world tends to increase (Rosegrant et al., 2009; Jaeger et al., 2013; Hejazi et al., 2014; Hoekstra, 2014). “To reduce the number of people suffering from water scarcity” is one of the 17 targets in Sustainable Development Goals set by the United Nations (2015), and is also high on the policy agendas of many state and local governments.

Water scarcity can be physical or economic. Physical water scarcity occurs when the water demand in one region exceeds the natural available resource. Economic water scarcity occurs when a region fails to provide water in an accessible manner due to a lack of infrastructure or technology to draw water from nature (UNDP, 2006). Economic water scarcity occurs more often in less developed countries/regions. This study focuses on physical water scarcity, and in the following text, physical water scarcity is referred to as water scarcity for short. Many previous studies have assessed water scarcity degrees on multiple levels, providing knowledge

on how water demand mismatches water resources availability on the city, country and global scales (e.g., Mekonnen and Hoekstra, 2016; Wada et al., 2011; Munia et al., 2016; Hanasaki et al., 2013; Yin et al., 2017; Munia et al., 2018), indicating a great challenge of coping with water scarcity by humans.

Water scarcity varies over time as a result of a number of natural and socio-economic changes (e.g., Alcamo et al., 2003; Jiang et al., 2009; Hanasaki et al., 2013; Distefano and Kelly, 2017; Bijl et al., 2018). While it is recognized that the changing water scarcity was attributed to population growth and economic development (e.g., Florke et al. 2013; Wada et al. 2013; Haddeland et al. 2014; Kummu et al. 2014; Wada et al. 2016), varying hydro-climatic conditions and climate change (e.g., Schewe et al. 2014; Hanasaki et al., 2013; Kiguchi et al. 2015; Arenas-Sanchez et al. 2016;), effects of different factors on variations of water scarcity were rarely disentangled and quantified based on historical water scarcity evidence. A thorough analysis of the reasons behind the inter-annual variability of water scarcity conditions is the key to understand impacts of different driving factors and identify the major determinants, and is therefore a prerequisite for successful adaptation or mitigation of water scarcity (Mason and Calow, 2012). A first attempt was made to separate impacts of socioeconomic change and hydro-climatic variability on global water scarcity events using the “one-factor-at-a-time” method (Veldkamp et al., 2015). In this study, the effect of socioeconomic change was identified under fixed hydro-climatic condition, and the impact of hydro-climatic factor was analyzed under fixed socioeconomic conditions. In order to meet the “completeness” requirement (that is, the residual, which refers to the difference between the total water scarcity change and the sum of the determinant effects, is equal to 0), the residual is attributed to the two factors

proportional to their effects identified above, which might neglect the interactive effect of the two factors. In addition, a decomposition of water scarcity variability into a number of detailed effects (rather than lumped hydro-climatic and socioeconomic factors), which is essential for providing in-depth insight for policy making, is missing in Veldkamp et al. (2015). Thus, there is a critical need to develop a more rigorous method for quantifying contributing effects of a number of factors to water scarcity variability.

This study presents a new analytical methodology for decomposing temporal variations of water scarcity, which is measured by two complementary indicators, i.e., water crowding index (WCI) and water withdrawal to availability ratio (WTA), into effects of a number of hydro-climatic and socioeconomic factors. The structural decomposition analysis (SDA), which is conventionally used for examining governing factors of temporal changes of economic variables and environmental footprints in an input-output (IO) context (e.g., Dietzenbacher and Los, 1998; Zhang et al., 2012; Sun, 2019), is applied to investigate the driving mechanism for historical water scarcity variations. The main contribution of this study lies in the development of a framework for decomposing water scarcity changes into a number of effects. To the best of the authors' knowledge, this is the first time that the SDA is used for water scarcity analysis and that contributions of a number of relevant socio-economic factors driving water scarcity level changes are quantified.

The methodology is then applied to water scarcity assessment in China's capital, i.e., Beijing, which has been subject to extreme water stress since 1990s. Previous water resources relevant studies in Beijing focused more on physical and virtual water transfers and water quality issues (e.g., Zhang et al., 2012; Zeng et al., 2013; Wang et al., 2017). In particular,

Zhang et al. (2012) analyzed Beijing's water footprint change, in which the SDA is used in the context of its conventional application area for footprint study. This study provides a detailed analysis on the driving factors of the trend and randomness of physical water scarcity. The quantification of different effects on water scarcity variations in Beijing allows for better understanding the driving mechanism of water scarcity conditions, based on which, policies are informed for sustainable water resources planning and management towards reduced water scarcity.

2 Case study and data

Beijing is located in the semi-arid and semi-humid climate zone in the north plain in China. (115.7°- 117.4°E, 39.4°- 41.6°N). It covers a total area of 16 410 km², and is the home of 21.7 million people. Beijing has been under great water pressures due to rapidly growing population and vigorous economic development (e.g., Zhang et al.2012; Zeng et al., 2013; Wang et al., 2017; Sun, 2019). Main water data used in this study include local available freshwater resource, sectoral water uses, reclaimed water uses and south-to-north transferred water in Beijing during 1997- 2016 (Beijing Water Authority, 1997-2016). Local available freshwater resource is comprised of two parts, i.e., locally generated freshwater resource and water resource from upstream catchments. Sectoral water uses consist of agricultural, industrial, domestic and ecological water uses. Ecological water use refers to water used for irrigating urban green spaces and replenishing dry rivers and lakes. As Beijing has long been under high water stress, reclaimed water and south-to-north transferred water have been increasingly used to supplement the local available water resource.

Socio-economic data including population, GDP and sectoral GDP (agricultural, industrial and tertiary GDP) during 1997 - 2016 are retrieved from China statistical yearbooks (National Bureau of Statistics of China, 1997-2016). Times series of socio-economic data in Beijing are displayed in Fig. 1.

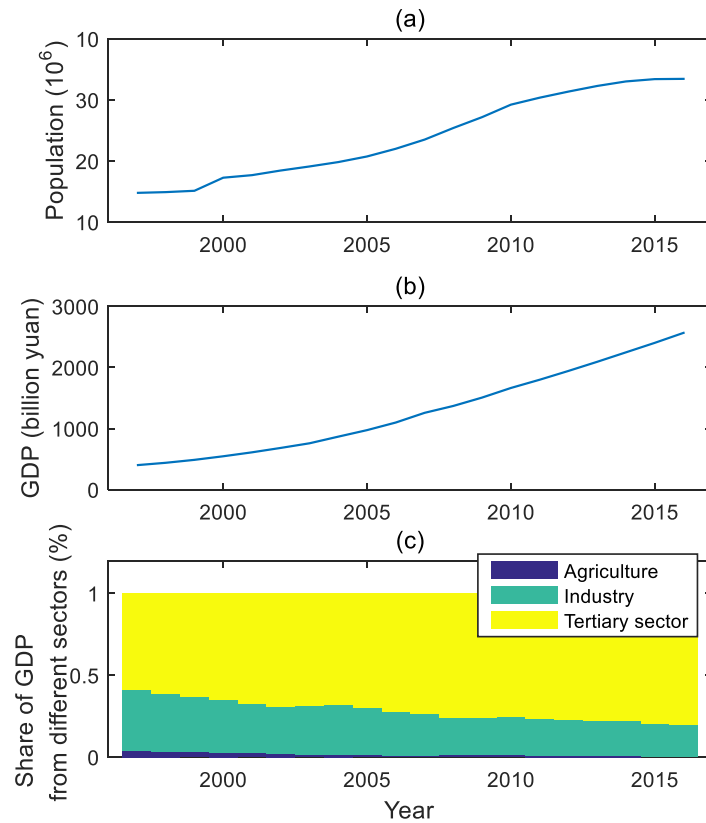


Figure 1. Socio-economic data from 1997 to 2016 in Beijing: (a) Population; (b) Total GDP; (c) GDP structure.

3 Methodology

3.1 Mann-Kendall method and Sen's slope

The Mann-Kendall method (Kendall, 1955; Mann, 1945), a nonparametric trend detection test extensively applied in climatology and hydrology (e.g., Gocic and Trajkovic, 2013; Sun et al.,

2017), is used in this study to examine whether a variable exhibits a trend. It tests the null hypothesis H_0 of trend absence in the vector $[x_1, x_2, \dots, x_n]$ against the alternative of a trend. The test statistic S is defined as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (1)$$

where $\text{sgn}(x_j - x_k)$ equals -1, 0 and 1 when x_j is larger than, equal to and smaller than x_k , respectively. Under the null hypothesis, S is asymptotically normally distributed. Kendall's tau that follows a standard normal distribution is calculated based on S . The P -value of Kendall's tau is then compared with a predefined significance level (5% in this study) to determine whether a trend exhibits. If the existence of a trend is confirmed, the Sen's slope (Sen, 1968) is used to assess the magnitude β :

$$\beta = \text{Median}((x_j - x_i)/(j - i)) , \quad i < j \quad (2)$$

where Median (y_k) represents the median value of y_k .

3.2 Water scarcity indicators

Physical water scarcity can be population driven or demand driven. While most of previous studies focused on only one water scarcity indicator (Veldkamp et al., 2015), analysis of this study is based on assessment of the two complementary water scarcity measurements, i.e., WCI and WTA. Population-driven water scarcity refers to insufficient water availability per person, which can be measured by WCI:

$$WCI = \frac{WR}{pop} \quad (3)$$

where WR and pop denote local available freshwater resource and population, respectively. WR corresponds to locally generated water resource and upstream water resource available for

water uses in the study region (Wada et al., 2011; Mekonnen and Hoekstra, 2016; Munia et al. 2018). Demand-driven water scarcity refers to over-use of water by all sectors and people relative to available water resource (Falkenmark et al., 1997; Kummu et al., 2014), which can be measured by WTA:

$$WTA = \frac{WW}{WR} \quad (4)$$

where WW denotes total water withdrawal from local available freshwater resource. Water uses from other particular sources other than local resource are eventually subtracted from the total water uses in Beijing, as these water uses alleviate the demand that has to be met from local available freshwater, following previous studies (Oki and Kanae, 2006; Wada et al., 2011). As reclaimed and south-to-north transferred water are increasingly used as supplements to local resource in Beijing, water withdrawal from local available freshwater resource can be calculated as:

$$WW = \sum_i WU_i - WU_{\text{reclaimed}} - WU_{\text{transfer}} \quad (5)$$

where WU_i refers to water uses in different sectors ($i=1, 2, 3, 4$ for agricultural, industrial, domestic and ecological uses, respectively), $WU_{\text{reclaimed}}$ and WU_{transfer} denote water uses from reclaimed water and south-to-north transferred water, respectively.

Substituting Eq. (5) in Eq. (4), WTA can be written as the sum of a number of constitutional terms:

$$\begin{aligned} WTA &= \frac{WU_{1+2} + WU_3 + WU_4 - WU_{\text{reclaimed}} - WU_{\text{transfer}}}{WR} \\ &= WTA_1 + WTA_2 + WTA_3 - WTA_4 - WTA_5 \end{aligned} \quad (6)$$

Hence, WTA_1 , WTA_2 and WTA_3 are the parts of WTA attributed to agricultural & industrial water uses, domestic water use and ecological water use, respectively; WTA_4 and WTA_5 represent

water scarcity mitigation attributed to reclaimed and transferred water uses, respectively. Different levels of water scarcity are empirically defined based on WCI and WTA values (Vorosmarty et al., 2000; Wada et al., 2011; Falkenmark, 2013; Kiguchi et al., 2015): moderate water scarcity when WCI is below 1700 m³ per capita or WTA is over 0.2; significant water scarcity with WCI below 1000 m³ per capita or WTA over 0.4; and severe water scarcity with WCI below 500 m³ per capita or WTA over 0.7. It is worth noting that water scarcity levels based on WCI and WTA may be inconsistent, as these two indicators consider different socio-economic driving factors.

3.3 Structural decomposition analysis

Although mostly used for economic or environmental footprint analysis in an IO context, the application of SDA is not limited to IO based analysis (Hoekstra and van der Bergh, 2003). The SDA is able to decompose temporal changes of one variable Y into constitutional contributions from a number of variables X_i if $Y = \prod_i X_i$. A multitude of equivalent decomposition forms exist (Dietzenbacher and Los, 1998), as the decomposition can be executed based on either the base year value or end year value (Zhang et al., 2012). The number of the first-order decomposition possibilities is $n!$ with n factors of X_i . The mean of the effects of one factor from all possible decompositions is used to represent the specific effect of this factor (e.g., Sun, 2019). One of the decompositions for $Y = \prod_i X_i$ is:

$$\Delta Y = \Delta X_1 \prod_{i>1} X_{i,0} + X_{1,1} \Delta X_2 \prod_{i>2} X_{i,0} + \dots + \prod_{i<n} X_{i,1} \Delta X_n \quad (7)$$

where $\Delta Y = Y_1 - Y_0$, representing the temporal change of variable Y , with the subscript 1 and 0 denoting the base and end years, $\Delta X_i = X_{i,1} - X_{i,0}$, denoting the temporal change of variable X_i . Therefore, ΔY is broken down into i contributions in Eq. (7), with the term of

$\prod_{i < k} X_{i,1} \Delta X_k \prod_{i > k} X_{i,0}$ representing the contribution of X_k . Other decomposition forms can be obtained by applying Eq. (7) to each permutation of the indices set $\{1, 2, \dots, n\}$, and rewriting the n additive components in their original orders in the equation $Y = \prod_i X_i$. In comparison to the “one-factor-at-a-time” method (Veldkamp et al., 2015), the SDA meets the “completeness” requirement without additional residual attribution and can be flexibly used to decomposition of more than two effects.

3.4 Decomposition of water scarcity changes: effects of hydro-climatic variability and socioeconomic change

Water scarcity is time-dependent; it varies from year to year (Mekonnen and Hoekstra, 2016). Water scarcity level depends on both hydro-climatic and socioeconomic conditions (Eqs. 3 and 4). WR is a hydro-climatic relevant variable; pop and WW are associated with socioeconomic conditions for population-driven and demand-driven water scarcities, respectively. It is worth noting that overlapping exists in population-driven and demand-driven water scarcities, as demand-driven water scarcity may partly be driven by population growth. In this section, inter-annual water scarcity changes are broken down into contributions from hydro-climatic variabilities and socioeconomic development using the SDA. In Eq. (3), WCI can be regarded as the product of WW and $1/WR$. The two possible decompositions of the temporal change in WCI are:

$$\begin{aligned} \Delta WCI &= \Delta WR * \frac{1}{pop_1} + WR_0 * \Delta \frac{1}{pop} \\ \Delta WCI &= \Delta WR * \frac{1}{pop_0} + WR_1 * \Delta \frac{1}{pop} \end{aligned} \quad (8)$$

where $\Delta WCI = WCI_1 - WCI_0$, representing the change of WCI in two consecutive years, subscripts 0 and 1 indicate earlier and latter years, respectively, $\Delta WR = WR_1 - WR_0$, $\Delta \frac{1}{pop} = \frac{1}{pop_1} - \frac{1}{pop_0}$.

The two terms on the right side of Eq. (8) indicate the parts of ΔWCI that can be attributed to inter-annual hydro-climatic variability and socioeconomic change, respectively, i.e., changes of WR and $1/pop$ in two consecutive years. Similarly, the two decompositions of temporal change in WTA are:

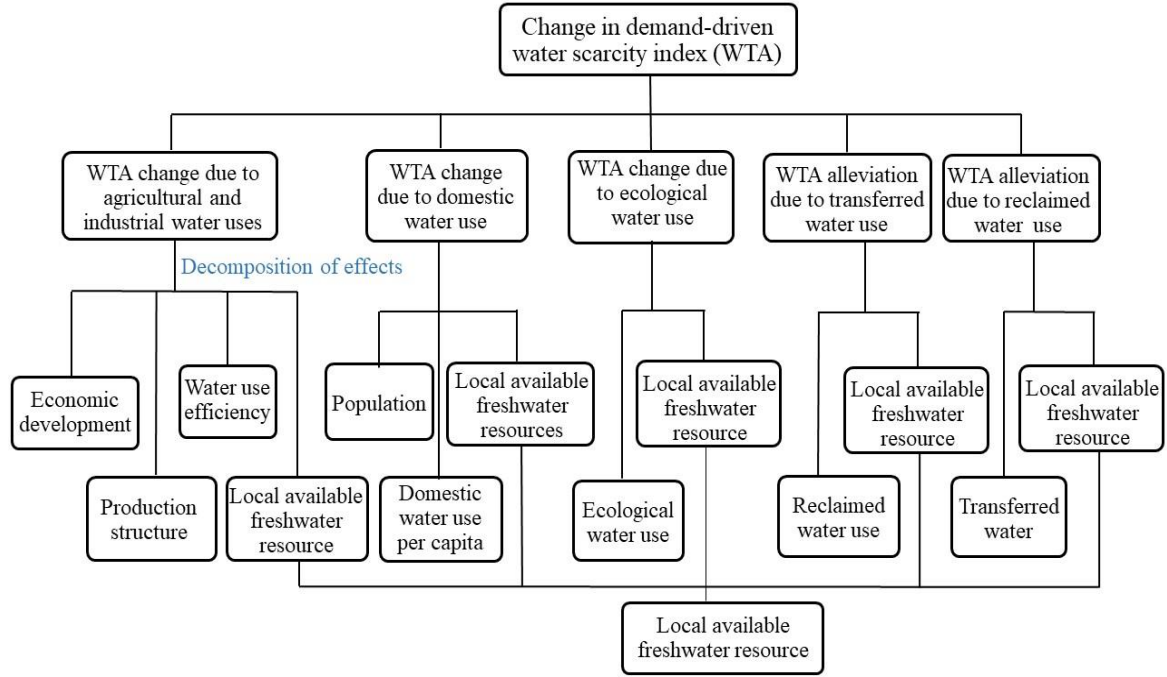
$$\begin{aligned}\Delta WTA &= \Delta WW * \frac{1}{WR_1} + WW_0 * \Delta \frac{1}{WR} \\ \Delta WTA &= \Delta WW * \frac{1}{WR_0} + WW_1 * \Delta \frac{1}{WR}\end{aligned}\tag{9}$$

where $\Delta WTA = WTA_1 - WTA_0$, representing the change of WTA in two consecutive years, $\Delta \frac{1}{WR} = \frac{1}{WR_1} - \frac{1}{WR_0}$, $\Delta WW = WW_1 - WW_0$. The two terms on the right side of Eq. (9) indicate the parts of ΔWTA attributed to inter-annual socioeconomic change and hydro-climatic variability, respectively, i.e., changes of WW and $1/WR$ in two consecutive years. While Veldkamp (2015) used the similar indicators and variables to represent water scarcity levels and relevant driving factors, the effects of hydro-climatic and socioeconomic variables are examined under the fixed socioeconomic and fixed hydro-climatic conditions, respectively.

3.5 Detailed decomposition for demand-driven water scarcity changes

As specified in Eq. (5), WW , which equals accumulated sectoral water demands minus water uses not from local available freshwater resource, can be expressed as a function of a few variables. Hence, a detailed decomposition of temporal changes of the demand-driven WTA is developed, to quantify relative importance of a series of socioeconomic factors as well as local available freshwater resource in determining inter-annual WTA changes. By doing this, the lumped socioeconomic impact in Eq. (9) is further broken down into effects of a number of underlying factors. The detailed decomposition for temporal WTA changes is illustrated in Fig.

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Figure 2. Detailed decomposition of temporal water stress changes

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Each term in Eq. (6) is written as the product of a number of factors:

$$\begin{aligned}
 WTA_1 &= \sum_{i=1,2} (GDP * \alpha_i * wi_i) * \frac{1}{WR} \\
 WTA_2 &= pop * wp * \frac{1}{WR} \\
 WTA_3 &= WU_4 * \frac{1}{WR} \\
 WTA_4 &= WU_{reclaimed} * \frac{1}{WR} \\
 WTA_5 &= WU_{transferred} * \frac{1}{WR}
 \end{aligned} \tag{10}$$

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where GDP represents annual GDP, the growth of which characterizes economic development,

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α_i are the shares of agricultural and industrial GDP when $i = 1$ and 2, respectively,

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characterizing the production structure, wi_i are water use intensities for agricultural and

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industrial production, i.e., the amount of water used for producing one monetary unit of

agricultural or industrial products, pop is population, and wp represents domestic water use per capita. For WTA_1 in Eq. (10), which is the product of four factors, there are $4! = 24$ first-order decomposition possibilities; for WTA_2 with three factors, there are $3! = 6$ first-order decomposition possibilities; for WTA_3 , WTA_4 and WTA_5 with two factors, there are 2 first-order decomposition possibilities. Similarly, the mean of the effects of one factor from all the decompositions is used to represent the effect of this specific factor. One of the decompositions of temporal change of WTA_1 is:

$$\begin{aligned} \Delta WTA_1 = & \sum_i (\Delta GDP * \alpha_{i,1} * wi_{i,1}) * \frac{1}{WR} \\ & + \sum_i (GDP_0 * \Delta \alpha_i * wi_{i,1}) * \frac{1}{WR} + \sum_i (GDP_0 * \alpha_{i,0} * \Delta wi_i) \\ & * \frac{1}{WR} + \sum_i (GDP_0 * \alpha_{i,0} * wi_{i,0}) * \Delta \frac{1}{WR} \end{aligned} \quad (11)$$

where $\Delta WTA_1 = WTA_{1,1} - WTA_{1,0}$, $\Delta GDP = GDP_1 - GDP_0$, $\Delta \alpha_i = \alpha_{i,1} - \alpha_{i,0}$, $\Delta wi_i = wi_{i,1} - wi_{i,0}$. The four terms on the right side of Eq. (11) indicate the parts of ΔWTA_1 attributed to changes in economic development, production structure, water use efficiency and local available freshwater resource, respectively. Similarly, ΔWTA_2 can be attributed to changes in population, domestic water use per capita and local available freshwater resource; ΔWTA_3 can be attributed to changes in ecological water use and local available freshwater resource; ΔWTA_4 can be attributed to changes in reclaimed water and local available freshwater resource; ΔWTA_5 can be attributed to changes in transferred water and local available freshwater resource. The decomposition equations are provided in supplemental file. Therefore, ΔWTA is decomposed into changes due to 9 factors, i.e., the economic development, production structure, water use efficiency in production, population, domestic

water use per capita, ecological water use, reclaimed water, transferred water and local available freshwater resource. The effect of local available freshwater resource on WTA is calculated as the sum of its contributions to ΔWTA_1 , ΔWTA_2 and ΔWTA_3 minus contributions to ΔWTA_4 and ΔWTA_5 , as shown in Fig. 2, which should be equivalent to its effect on ΔWTA obtained based on Eq. (9). This detailed decomposition allows for further disentangling effects of a number socioeconomic relevant variables, after quantifying the lumped socioeconomic effect, which facilitates understanding specific underlying reasons that lead to water scarcity level changes.

4 Results

4.1 Local available freshwater resource and water withdrawal in Beijing

Fig. 3 shows local available freshwater resource in Beijing in 1997- 2016, consisting of locally generated water resource and water resource from upstream catchments. Table 1 lists the trend detection results by the Mann-Kendall method. In the study period, Beijing's locally generated water resource presents a slightly increasing trend, likely due to combined effects of climate change, natural variability of climate as well as land use changes due to anthropogenic activities. However, a detailed investigation of reasons for this trend of Beijing's locally generated water resource is beyond the scope of this study. In contrast, upstream water resource exhibits a declining trend, due to increasing water exploitation along with population growth and economic development in upstream areas. As a result of these two opposing trends, Beijing's local available freshwater resource does not present a

significant trend. On average, locally generated and upstream water resources constitute 90.2% and 9.8% of Beijing's total local available freshwater resource, respectively.

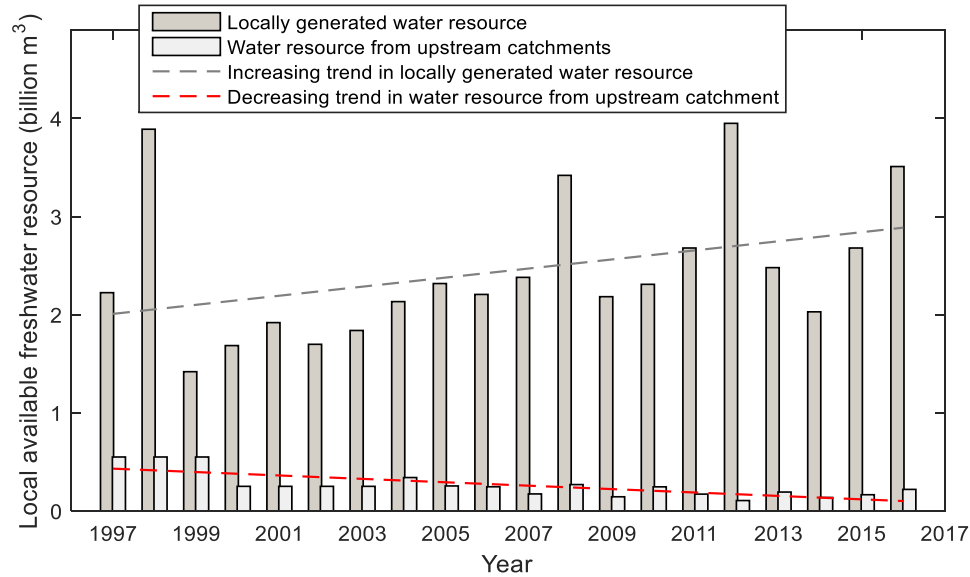


Figure 3. Local available water resource in Beijing in 1997-2016

Fig. 4(a) shows sectoral water uses in Beijing in 1997- 2016. Trend detection results for sectoral and total water uses are also given in Table 1. Agricultural and industrial water uses have witnessed significant declining trends. In contrast, domestic water and ecological water uses have showed significant increasing trends. The total water use in Beijing do not show a monotonic trend, varying between 3.47 and 4.17 billion m³ in the recent two decades. Fig. 4(b) shows reclaimed and transferred water uses in Beijing. Reclaimed water has been increasingly used since 2002. Transferred water use has an increasing trend since 2008 when the south-to-north transfer project started to provide water to Beijing. In 2016, reclaimed and transferred water uses constitute 49% of the total water uses in Beijing. Fig. 4(c) shows water withdrawal from local available freshwater resource in Beijing (i.e., total water use minus reclaimed and transferred water uses). Due to increasing reclaimed and transferred water uses,

water withdrawal from available water resource in Beijing exhibits a significant declining trend (Table 2). The Sen's slope of water withdrawal from local available water resource is estimated at 0.145 billion m³ per year.

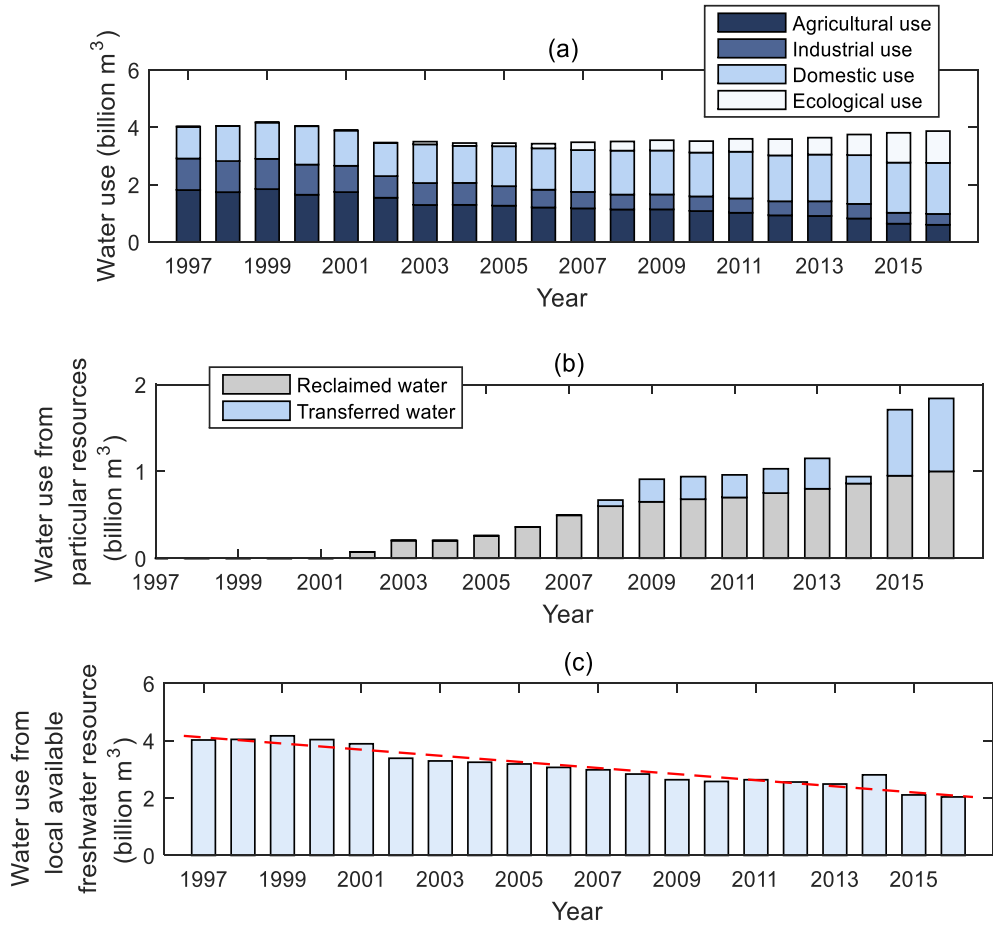


Figure 4. Water withdrawal in Beijing between 1997-2106: (a) sectoral water uses; (b) water uses from reclaimed and transferred water; (c) water use from local available freshwater resource

Table 1. Trend detection results in available water resources, water uses and water scarcity indices in Beijing in 1997-2016

	Variable	Kendall's tau	<i>p</i> -value (%)	Trend	Sen's slope (per year)
Water resources	Locally generated water resource (10 ⁹ m ³)	2.66	0.4	↑	0.067
	Water resource from upstream catchments (10 ⁹ m ³)	-3.70	1.1x10 ⁻²	↓	-0.013
	Local available freshwater resource, i.e., local generated and upstream water (10 ⁹ m ³)	1.98	2.4	-	-
Water uses and withdrawal	Agricultural water use (10 ⁹ m ³)	-5.74	4.7x10 ⁻⁷	↓	-0.060
	Industrial water use (10 ⁹ m ³)	-5.55	1.4x10 ⁻⁶	↓	-0.038
	Domestic water use (10 ⁹ m ³)	5.35	4.3x10 ⁻⁶	↑	0.033
	Ecological water use (10 ⁹ m ³)	5.65	8.2x10 ⁻⁷	↑	0.050
	Total water use (10 ⁹ m ³)	0.10	46.1%	-	-
	Water use from reclaimed water (10 ⁹ m ³)	5.74	4.7x10 ⁻⁷	↑	0.060
	Water use from transferred water (10 ⁹ m ³)	3.93	5.3x10 ⁻³	↑	0.022
	Water withdrawal from local available freshwater resource (10 ⁹ m ³)	-5.45	2.5x10 ⁻⁶	↓	-0.145
Water scarcity indices	WCI (m ³ per capita)	-1.78	3.7	↓	-2.4
	WTA (-)	-3.80	7.4x10 ⁻³	↓	-0.065

Note: ↑ and ↓ represents increasing and decreasing trends at 5% significance level, respectively.
 – indicates no trend at 5% significance level.

4.2 Water scarcity evolution in Beijing

Annual WCI and WTA values in Beijing during 1997-2106 are shown in Fig. 5. The WCI in Beijing varies between 100.8 and 356.4 m³ per capita (Fig.4 a), and the WTA distributes between 0.55 and 2.12 (Fig. 4 b). Beijing has been most often under severe water scarcity with WCI below 500m³ per capita and WTA over 0.7. The WTA is often over 1, implying that water demand cannot be met even if all local available water resource is exploited for different sectoral water uses. When WTA is over 1, water uses in Beijing partly relies on

exploitation of fossil groundwater. The Mann-Kendall test results indicate that both the WCI and WTA present significant declining trends (p -value = 3.7% and $7.4 \times 10^{-3}\%$, respectively, see Table 1). The Sen's slopes of the WCI and WTA are -2.4 m^3 per capita and -0.065 per year, respectively. Declining WCI indicates intensified population-driven water scarcity, whereas reduced WTA implies relieved demand-driven water scarcity. Contradicting water scarcity evolving trends based on WCI and WTA can be explained by different driving socioeconomic factors.

After subtracting the trends from the WCI and WTA values, the remaining parts present randomness. The randomness of the WCI and WTA is fitted to a number of typical probability distributions, including normal, log-normal, exponential, gamma, extreme value distributions. The Kolmogorov-Smirnov test results indicate that the random parts of both the WCI and WTA can be fitted to the extreme value distribution with the p -value below 1% (see Fig. 5b and 5d).

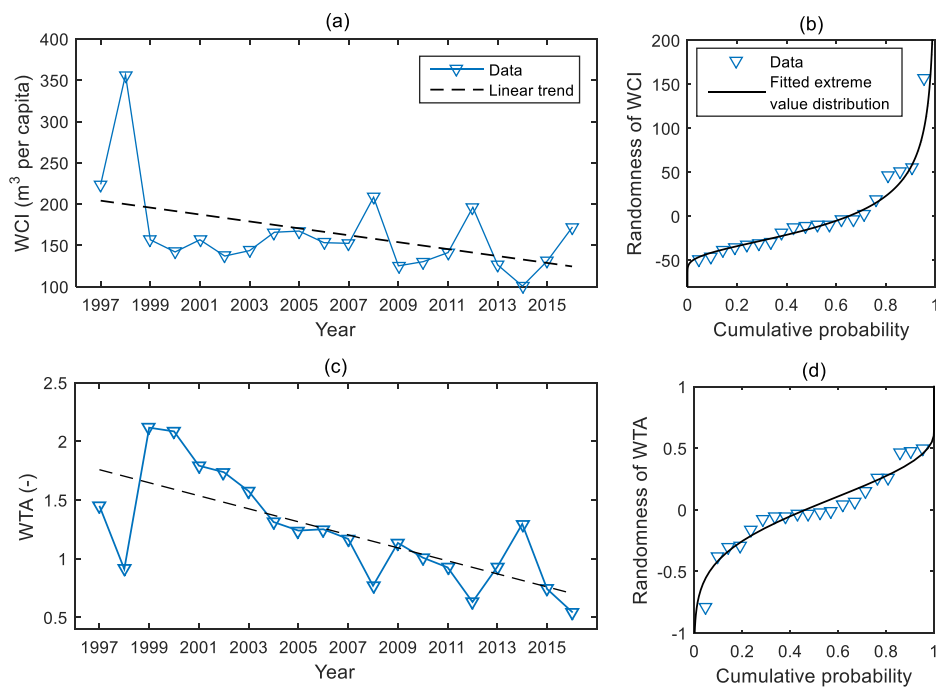


Figure 5. Linear trend and randomness of WCI and WTA in Beijing: (a) linear trend of WCI; (b) randomness of WCI can be fitted to the extreme value distribution; (c) linear trend of WTA; (d) randomness of WTA can be fitted to the extreme value distribution.

4.3 Effects of hydro-climatic variability and socio-economic change

Changes in WCI and WTA in consecutive years are decomposed into effects of hydro-climatic variability and socioeconomic change using Eqs. (7) - (8). Figs. 6 and 7 display the decomposition results for WCI and WTA, respectively. Table 2 summarizes statistics of different effects. From Fig. 6(a), annual changes of local available water resource (i.e., hydro-climatic variability) may exert positive or negative effect on WCI, whereas population growth (i.e., socio-economic change) always has a negative effect on WCI. Randomness of local available water resource leads to a large variation of WCI, ranging between -197.4 and 133.9 m³ per capita. The impact of population growth in individual years is much smaller, with its mean of absolute values one order of magnitude less than that of local available water resource. In Fig. 6(b), the cumulative effects of the two factors are displayed. Albeit relatively large effects attributed to local available water resource in individual years, the cumulative effect fluctuates around 0 because of alternative positive and negative inter-annual effects. In contrast, albeit small, the consistent negative effect of population growth aggravates WCI over the study period.

In Fig. 7(a), the effect of local available water resource on WTA presents large fluctuation between -0.545 and 1.160, while the factor of water withdrawal from local available water resource contributes to reducing WTA in a majority of years. The absolute values of effects of water withdrawal is only 1/4 that of local available water resource. In Fig. 7(b), the

cumulative effect of local available water resource fluctuates around 0, and that the
cumulative effect of water withdrawal tends to relieve WTA.

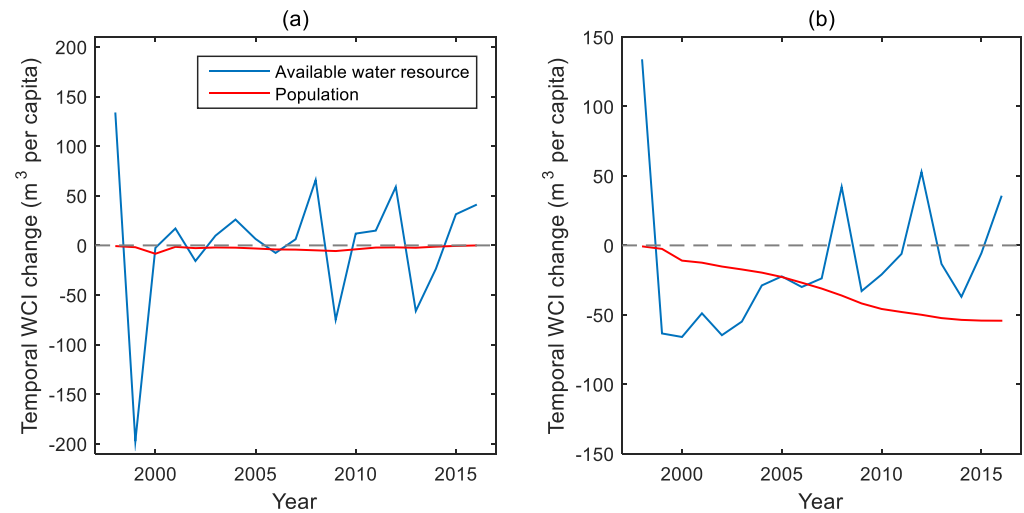


Figure 6. Effects of local available water resource and population on temporal WCI changes
in Beijing: (a) annual effects; (b) cumulated effects.

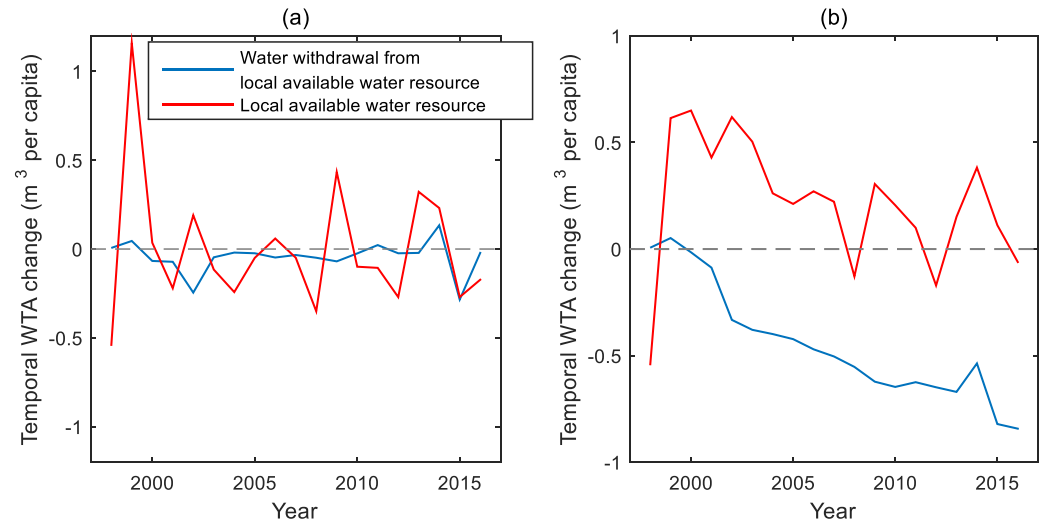


Figure 7. Effects of water withdrawal and local available water resource on temporal WTA
changes in Beijing: (a) annual effects; (b) cumulated effects.

Table 2. Statistics of hydro-climatic variability and socioeconomic change on temporal
changes of WCI and WTA in Beijing

Factor	Factor	Mean	Standard deviation	Range	Cumulative effect
WCI (m ³ per capita)	Local available water resource (hydro-climatic variability)	1.9	66.5	[-197.4, 133.9]	35.1
	Population (socioeconomic change)	-2.9	2.0	[-8.4, -0.07]	-54.2
WTA (-)	Water withdrawal from local available water resource (socioeconomic change)	-0.04	0.091	[-0.28, 0.13]	-0.84
	Local available water resource (hydro-climatic variability)	-0.003	0.371	[-0.55, 1.16]	-0.06

4.4 Detailed decomposition of temporal changes of water scarcity

Changes in WTA in consecutive years are decomposed into effects of nine factors based on the detailed decomposition method described in section 2.5. Fig. 8 shows annual and accumulative effects of different factors, and Table 3 summarizes the statistics of the effects. Fig.8 (a) shows that effects of one specific factor in individual years fluctuates over time. The variation of the effect of the local available water resource is the largest, with the standard deviation one order of magnitude larger than other socioeconomic effects. While local available water resource possibly exerts positive or negative impact in different years, all the socioeconomic factors tends to have consistent impacts (either positive or negative) on the WTA over the study period. Fig. 8(b) shows the cumulative effects of different factors on the WTA. The eight detailed socioeconomic factors are categorized into two groups, i.e., factors exaggerating WTA and factors alleviating WTA. Three factors, i.e., the economic development, population and ecological water use, contribute to exaggerating the WTA. The effect of economic development is the largest. The effect of population growth on aggravating WTA is consistent to its effect on aggravating water scarcity indicated by WCI (Table 2). In

contrast, changes in industrial structure, water use efficiency, domestic water use per capita, reclaimed and transferred water uses contribute to the reduction of the WTA. The largest offsetting force for WTA is industrial structure upgrade, followed by improved water use efficiency. The total effect of factors alleviating WTA outweighs the effect of factors exacerbating WTA. The total effect from the 8 socioeconomic factors is equal to the lumped impact of water withdrawal from local available water resource on WTA in Table 3.

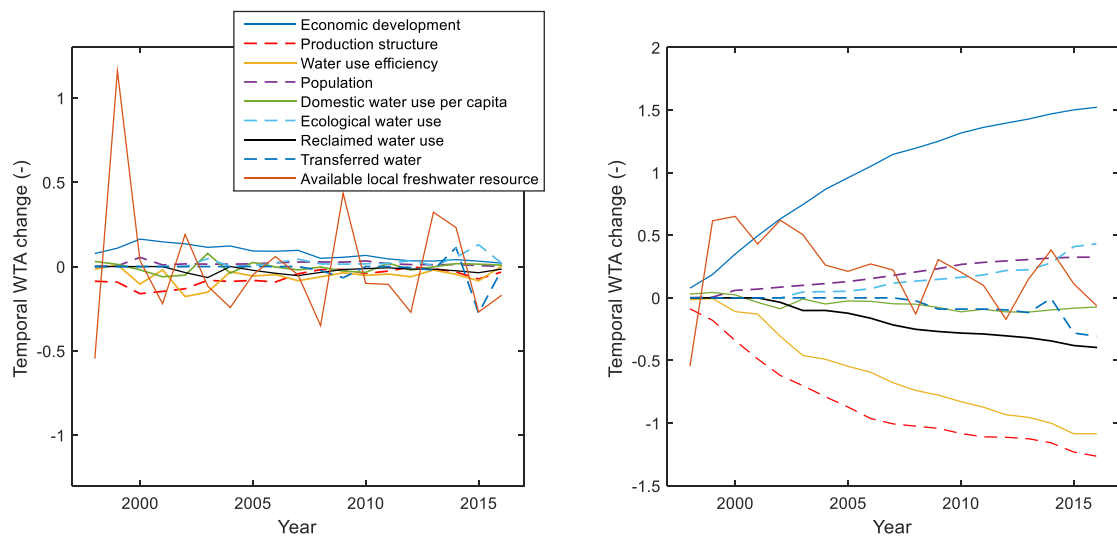


Figure 8. Detailed decomposition results of temporal WTA changes in Beijing: (a) annual effects of different factors; (b) cumulated effects of different factors

Table 3. Statistics of different effects on temporal changes of WTA in Beijing

Factor	Mean	Standard deviation	Range	Cumulative effect
Economic development	0.080	0.043	[0.021, 0.163]	1.52
Economic structure	-0.067	0.047	[-0.161, -0.003]	-1.26
Production water use efficiency	-0.057	0.048	[-0.178, 0.010]	-1.08
Population	0.017	0.013	[0.001, 0.055]	0.32
Domestic water use per capita	-0.004	0.033	[-0.060, 0.078]	-0.074
Ecological water use	0.023	0.031	[0, 0.130]	0.43
Reclaimed water use	-0.021	0.019	[-0.065, 0]	-0.40
Transferred water use	-0.016	0.071	[-0.276, 0.113]	-0.31
Local available water resource	-0.003	0.371	[-0.546, 1.161]	-0.06

5 Discussion and policy implications

5.1 Declining demand-driven water scarcity trend and its drivers

Beijing is faced with severe demand-driven water scarcity. As the capital of China, it attracts migration, commercial and noncommercial organizations, and suffers greatly from environmental degradation due to water shortage. Hence, large efforts have been made to lessen local water scarcity in recent years. As a result, Beijing's WTA presents a slightly declining trend, albeit the growing population and economy. According to the decomposition analysis that separates effects of hydro-climatic variability and socioeconomic change, overall, the declining trend in WTA is mainly driven by the socio-economic change.

The detailed SDA further identifies the relative importance of specific socio-economic factors in contributing to the declining trend of the WTA. The main forces driving the declining WTA are the industrial structure upgrade, improved water use efficiency, reclaimed and transferred water uses and domestic water saving. Industrial structure has been upgraded by encouraging high-tech and less natural resources intensive industries. The scale of agriculture in Beijing has been remarkably reduced, the share of which in terms of GDP has been decreased from 4.7% in 1997 to 0.5% in 2016 (Fig. 1). The proportion of high value added tertiary sector has been increased from 54.5% in 1997 to 80.2% in 2016. Agricultural and industrial water use efficiencies have been improved. Water intensive crops such as rice and many vegetables are not allowed to grow locally, but replaced mostly by rainfed corns (Zhang et al., 2012). Efficient water use technologies such as drip irrigation and sprinkling irrigation have been widely applied in croplands instead of traditional irrigation. Water intensive

industries have been prohibited since 1990s; and existing water intensive factories have been moved out of Beijing gradually (Zhang et al., 2012). Industrial water recycling has been encouraged to reduce the net intake of water for factories. In addition, local available water resource supplements, i.e., reclaimed and transferred water, have played a key role in alleviating Beijing's water scarcity. Reclaimed water, often for selected domestic water uses (e.g., toilet flush and car washing) and ecological water uses, has been increasingly used in Beijing since 2002. In order to encourage reclaimed water use, pricing instrument has been designed; wastewater producers and water consumers would receive penalty for violation of water reclamation and reuse policies in Beijing (Chang et al., 2013). South-to-north water transfer is an important national strategic project that aims at optimizing water resources allocation across basins. Since the start of the project in 2002, the state has made enormous investment in both human and material resources to transfer water from south to north. Lastly, domestic water saving has been achieved by implementing stepwise water price and applying water efficient appliances. Per capita domestic water use has been decreased by 62%, from 205.2 m³ in 1997 to 78.2 m³ in 2016.

5.2 Factors leading to increased water scarcity

The WCI results suggest that population growth leads to decreasing WCI, which has aggravated population-driven water scarcity. The population has increased by 1.8 times, from 12.4 million in 1997 to 21.7 million in 2016 (Fig. 1). Although the WTA has shown an overall decreasing trend, the detailed SDA results reveals that a few particular socioeconomic factors, including economic development, population growth and ecological water use, contribute to intensifying WTA in Beijing. Beijing has witnessed rapid economic

development during the study period with GDP increased by nearly 6.4 times, from 401.3 billion Chinese yuan in 1997 to 2566.9 billion yuan in 2016 (equivalent value in 2016). Economic development and population growth certainly require more water, resulting in more severe water scarcity. In the meantime, the fraction of urban green areas in Beijing has been increased greatly from 34.2% in 1997 to 48.4% in 2016. Increasing amounts of water have been discharged into rivers, lakes and artificial water bodies to recover or improve functioning of aquatic systems. Ecological water use has increased from 0.01 billion m³ in 1997 to 1.0 billion m³ in 2016. Such an abrupt increase of ecological water demand can be explained by the fact that the environment is more valued when wealth grows.

5.3 High randomness of water scarcity due to local available water resource

Annual WCI and WTA in Beijing present high randomness, which can mainly be attributed to natural water availability. Annual local available water resource fluctuates in a wide range between 1.94 and 4.44 billion m³ in 1997-2016, due to high natural variability of climatic and hydrological factors. In 1999 when Beijing received only 267 mm precipitation, about 46% of the long-term average of 585 mm per year, extreme water scarcity occurred with WCI 156.8 m³ per capita and WTA 2.12. In this driest year, annual WCI change attributed to local available water resource was as high as 197.4m³ per capita, and annual WTA change attributed to local available water resource was 1.16. The variability of local available water resource has dominated effects of other factors in determining WCI and WTA changes in two consecutive years. In the study period of two decades, hydro-climatic variability has only caused randomness of the WCI and WTA, but not a trend.

5.4 Policy implications

Assessment of a region's water scarcity degree and examination of underlying driving factors are essential for better understanding local water resource problems and challenges, and for further developing mitigation and adaptation strategies. The findings of this study aid in informing relevant policies towards sustainable water resources management and reduced water scarcity.

Albeit a decreasing trend presented in WTA, Beijing has long been under severe water scarcity according to both WCI and WTA. Fossil groundwater has been exploited to meet exceeding water demand over available renewable resource, which is unsustainable. The groundwater table in Beijing and surrounding areas has declined over 10 meters since 1980s (Fang et al., 2018). Continued descending groundwater table has caused a series of adverse environmental impacts such as land subsidence and ecosystem degradation (Xia et al., 2007). Therefore, it is urgent to take effective countermeasures to further mitigate water scarcity in Beijing.

Factors contributing to alleviating Beijing's water scarcity should be enhanced. Given limited local available water resource and extremely severe water scarcity faced by Beijing, particular water resources use as local freshwater resource supplement should be further exploited. While the amount of reclaimed water is curbed due to wastewater availability, south-to-north transferred water has more potential to be increased. However, attention needs to be paid to assure that water transfer would not result in eco-environmental degradation in southern regions. Appropriate eco-compensation mechanism should be established to reflect water resource scarcity as well as ecosystem and environmental costs in order to avoid unnecessary water use

increases in Beijing. Besides, Beijing has the advantage of developing and applying new technologies and institutional management strategies to further optimize water use structure and improve water use efficiency. While step water pricing has been implemented for domestic and industrial water uses, the agricultural water price is generally low, unable to reflect water resource scarcity. It is thus important to reform agricultural water pricing to encourage demand-side water saving (Jiang et al., 2009). People's behavior change should be encouraged to achieve water saving.

As population and economic growth tend to exaggerate water scarcity in Beijing, future urban planning should prioritize the water resources carrying capacity. Policies restricting rapid population growth and industrial development should be implemented in Beijing. In the background of integrated development of the Greater Beijing area, the water resources allocation should be optimized across urban and surrounding areas. In the meantime, ecological water use saving is critical, as increasing ecological water use is one of the main reasons for increasing water withdrawal. In construction of new irrigated urban green spaces, rain-fed plants should be considered for afforestation instead of water consuming vegetation in the city. Artificial aquatic landscapes, which requires water replenishment, should also be avoided in the urban planning stage.

As the variability of local available water resource leads to high randomness of water scarcity degrees in Beijing, it is vital to allocate inter-annual water resources to reduce extremely high water stress in low-flow years. Optimal uses of rivers, lakes, reservoirs, and groundwater aquifers allow for reduction of inter-annual variations of available water resource, because water can be stored in these spaces in relatively wet years and released in dry years. This

requires an integrated regulation of both surface and ground water systems for water supply management on the watershed scale.

6 Conclusions

This study addresses underlying driving factors for annual water scarcity variability. Both population-driven and demand-driven water scarcity degrees are assessed. A methodology for decomposing temporal water scarcity changes based on the SDA method is developed to attribute water scarcity changes into constitutional effects. A detailed decomposition framework is developed in this study to quantify the effects of a number of socioeconomic factors contributing to water scarcity level changes. The methodology is applied to water scarcity conditions assessment in Beijing to investigate relevant evolving properties.

Beijing has long been faced with severe water scarcity. However, the two complementary water scarcity indicators, i.e., WCI and WTA, show contradicting temporal water scarcity trends in the last two decades. WTA based demand-driven water scarcity shows a decreasing trend as a result of many water demand management measures implemented in Beijing, whereas WCI, a simple indication of water availability per person, tends to decrease, showing an aggravating water scarcity trend due to population growth.

The effect of the lumped socioeconomic change is further broken down into impacts of a number of factors. Detailed decomposition reveals that the declining trend of Beijing's WTA is mainly attributed to the industrial structure upgrade, improved water use efficiency, water uses of reclaimed and transferred water and domestic water saving. The accumulated effects of

these five factors on the WTA in 1997-2016 are estimated as -1.26, -1.08, -0.40, -0.31 and -0.07, respectively. In contrast, three other socioeconomic relevant factors, including the economic development, population growth and increasing ecological water use, contribute to aggravating Beijing's WTA. Their accumulated effects on changing the WTA are 1.52, 0.43 and 0.32, respectively. These positive effects offset the above-mentioned negative effects.

High randomness is present in both WCI and WTA, mainly attributed to natural variability of local available freshwater resource. The effect of water resources availability dominates other effects on WCI change in two consecutive years, whereas its accumulated long-term effect is negligible.

Albeit a decreasing demand-driven water scarcity trend, Beijing's water supply often relies on fossil groundwater exploitation. Water scarcity alleviation in Beijing is urgent in order to achieve sustainable use of water resources. Relevant policies are recommended, highlighting the importance of enhancing water demand management that benefits a reduction of water withdrawal from local available water resources. It is also essential to allocate inter-annual water resources to reduce extremely high water stress in low-flow years.

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Appendix A. Equations for detailed decomposition of WTA (water withdrawal to availability ratio)

WTA is expressed as the sum of WTA_i ($i = 1, 2, 3$) minus WTA_i ($i = 4, 5$). Decomposition equation for change in WTA_1 is provided in the main text. One of the decompositions of temporal change in WTA_2 can be written as:

$$\begin{aligned}\Delta WTA_2 = & \Delta pop * wp_1 * \frac{1}{WR} \\ & + pop_0 * \Delta wp * \frac{1}{WR} \\ & + pop_0 * wp_0 * \Delta \frac{1}{WR}\end{aligned}\tag{A1}$$

where $\Delta WTA_2 = WTA_{2,1} - WTA_{2,0}$, $\Delta pop = pop_1 - pop_0$, $\Delta wp = wp_1 - wp_0$. The three terms on the right side of Eq. (A1) indicate the parts of ΔWTA_2 attributed to population, domestic water use per capita and available freshwater resource, respectively. One of the decompositions of change in WTA_3 is:

$$\Delta WTA_3 = \Delta WU_4 * \frac{1}{WR_1} + WU_{4,0} * \Delta \frac{1}{WR}\tag{A2}$$

where $\Delta WTA_3 = WTA_{3,1} - WTA_{3,0}$, $\Delta WU_4 = WU_{4,1} - WU_{4,0}$. The two terms on the right side of Eq. (A2) indicate the parts of ΔWTA_3 attributed to ecological water use and local available freshwater resource, respectively.

One of the decompositions of change in WTA_4 is:

$$\Delta WTA_4 = \Delta WU_{reclaimed} * \frac{1}{WR_1} + WU_{reclaimed,0} * \Delta \frac{1}{WR}\tag{A3}$$

where $\Delta WTA_4 = WTA_{4,1} - WTA_{4,0}$, $\Delta WU_{\text{reclaimed}} = WU_{\text{reclaimed},1} - WU_{\text{reclaimed},0}$. The two terms on the right side of Eq. (A3) indicate the parts of ΔWTA_4 attributed to reclaimed water use and local available freshwater resource, respectively.

One of the decompositions of change in WTA_5 is:

$$\Delta WTA_5 = \Delta WU_{\text{transferred}} * \frac{1}{WR_1} + WU_{\text{transferred},0} * \Delta \frac{1}{WR} \quad (A4)$$

where $\Delta WTA_5 = WTA_{5,1} - WTA_{5,0}$, $\Delta WU_{\text{transferred}} = WU_{\text{transferred},1} - WU_{\text{transferred},0}$. The two terms on the right side of Eq. (A4) indicate the parts of ΔWSI_5 attributed to transferred water use and local available freshwater resource, respectively.